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Ω_b via Oort's Method

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ABSTRACT

The baryon density of the universe is equal to the product of the baryon-to-light ratio, M_b/L, and the luminosity density, j. We estimate M_b/L as the sum of the masses of the X-ray gas and the visible stars in a rich cluster of galaxies divided by the luminosity of the cluster galaxies in precisely the same sky aperture. We evaluate the gas-to-light ratio derived from the EMSS detect cell flux and the CNOC cluster redshift survey galaxies. After making an aperture correction to an effective overdensity of $500\rho_c$, we find that $\Omega_{gas} = 0.012 - 0.016h^{-3/2}$, depending on the galaxy fading correction. Adding in the galaxy baryons at a mass-to-light ratio of $5\,\mathrm{M}_\odot/\mathrm{L}_\odot$, equivalent to $\Omega_* = 0.003h^{-1}$, we find that $\Omega_b = 0.015 - 0.019$ for $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (or $0.040 - 0.051$ for $H_0 = 50$). Expressed as the baryon to photon ratio, η, this corresponds to $\eta = 4.0 - 5.2 \times 10^{-10}$ ($H_0 = 100$) and is in the mid-range of values from other methods. The individual clusters have a dispersion about the mean Ω_{gas} of 40%, and the χ^2 of the 14 clusters is consistent with the hypothesis that the gas-to-light ratio is a universal constant. If we ignore the light of the cD, the variance increases by a factor of three. After the radial segregation of gas and light within a cluster is taken into account, these statistics indicate that there is little variation of the gas-to-light ratio from cluster to cluster over the 0.2 to 0.55 range in redshift.

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1. Introduction

The baryon density of the Universe, $\Omega_b = \rho_b/\rho_c$, is a fundamental cosmological parameter. The ratio of the baryon density to the photon density in the cosmic background radiation, $\eta = 273 \times 10^{-10}\Omega_b h^2$ (for the observed CBR temperature), effectively measures the matter-anti-matter asymmetry at a very early time, likely when the universe was (re-)heated in the earliest moments of the Big Bang. Much later in the expansion of the universe, when it is a few minutes old, nuclear reactions assemble the light elements. The theory of Big Bang Nucleosynthesis (BBN) predicts the abundances of the light elements given the single parameter, η, and a knowledge of the number of types of neutrinos. Consequently, given observations that can be used to infer the primordial abundances of H, its isotope D, He and Li, the BBN theory predicts a value of Ω_b for consistency. The current measurements imply $\Omega_b = 0.007 - 0.024h^{-2}$ (Walker *et al.* 1991, Copi, Schramm & Turner 1995, Hogan 1997, Schramm & Turner 1997). The Helium abundances point toward relatively low values of Ω_b (*e.g.* Steigman 1997, Hogan, Olive & Scully 1997). Deuterium, as seen in conjunction with Hydrogen in high redshift absorption line systems, is currently a somewhat controversial indicator. Depending on the details of line identification and strength measurements, Deuterium favours either an Ω_b similar to that obtained from Helium (Songaila *et al.* 1994, Carswell *et al.* 1994) or a value near the upper end of the confidence range (Tytler, Fan & Burles 1996). For the values of Ω_b under discussion, the primordial Lithium abundance favours the low to mid Ω_b range but falls near a minimum of the predicted abundances so has reduced power to discriminate.

Another approach to Ω_b measurement via Lyman α clouds can be used to estimate Ω_b. These measurements rely on further assumptions, mainly the ionizing flux and the velocity distribution of the absorbing gas, which are constrained through other data and models. The result of the two model analyses is that $\Omega_b h^2 \geq 0.017$, which is consistent with the high Ω_b (Rauch *et al.* 1997, Weinberg *et al.* 1997).

High velocity dispersion galaxy clusters have long been recognized as powerful indicators of cosmological parameters. Measurements of the galaxy distribution and velocity dispersions in clusters show that the galaxies and the total mass have statistically identical distributions over the virialized region (Carlberg, Yee & Ellingson 1997, Carlberg *et al.* 1997a, Carlberg *et al.* 1997c). Furthermore, there is relatively little differential evolution between cluster and field galaxies (Lin *et al.* in preparation, Carlberg, Yee & Ellingson 1997). In these controlled circumstances one can use with confidence Oort's method (Oort 1958, Gott & Turner 1976) to estimate the mass density parameter of the universe, $\Omega_M = M/L \times j/\rho_c$, where M/L is the total cluster mass to light ratio, corrected for differential evolution, j is the field luminosity density and ρ_c the critical density. The same method can be used to measure $\Omega_b = (M_{gas} + M_{stars})/L \times j/\rho_c$. In both cases one measures only those components of the mass that are sufficiently cool that they cannot escape the gravitational field of 1000 $\mathrm{km\,s^{-1}}$ clusters.

The ratio of the gas mass to the total mass inside some radius in a cluster, f_g, (hereafter

referred to as the gas-to-mass ratio), calculated or normalized over the full virialized volume of the cluster, is expected to be nearly equal to the cosmic mean value, although this remains to be empirically established. It has long been known that f_g is 10-30% (*e.g.* Ku *et al.* 1983, Edge & Stewart 1991), but only recently has the precision of both f_g measurements and the BBN prediction become sufficient that a clear discrepancy between f_g and Ω_b/Ω_M with $\Omega_M = 1$ emerged (White *et al.* 1993, White & Fabian 1995, Myers *et al.* 1997). The approach to measuring Ω_b here is similar to that used by Steigman & Felten (1995, see also Myers *et al.* 1997), but has the innovation that we bypass the problem of measuring the cluster mass. That is, we use Oort's method, $\Omega_b = M_b/L \times j/\rho_c$. This is a direct measurement of Ω_b with minimal assumptions and a minimal error budget. Because Ω_M is also estimated with Oort's method, our Ω_b and Ω_M will move up or down together in the presence of a common, undetected, systematic error.

A critical consistency test of the assumption that Ω_b is faithfully represented by cluster baryons is that the Ω_b of individual clusters does not vary beyond the statistical confidence range. The situation with the gas-to-mass ratio is not clear at the moment, although it seems likely that much of the variance comes from the various complications in estimating masses (White & Fabian 1995). Here we can examine the variance of the ratio of cluster gas mass to cluster luminosity (hereafter the gas-to-light ratio) within our observed region to test for consistency with a universal ratio.

The next section of the paper describes our calculation of the gas mass within the EMSS "detect cell". Because the X-ray luminosity depends on the square of the emitting mass, it is relatively insensitive to the details of the emission modeling. The total light within the same aperture, both with and without the cD included, is a straightforward sum over the observed galaxies. The resulting gas-to-light ratio needs to be corrected for a well known aperture effect. In Section 3 we calculate the product of the gas-to-light ratio with the luminosity density at the same mean redshift to give the gas component of the baryons, to which we add our estimate of the stellar baryons to give the Ω_b of all the visible baryons. We conclude with a discussion of the strengths and weaknesses of this result and the prospects for improvement. All calculations in this paper take $H_0 = 100h\,\mathrm{km}\,s^{-1}$ and $q_0 = 0.1$.

2. EMSS/CNOC Cluster Gas-to-Light Ratios

The Canadian Network for Observational Cosmology (CNOC) redshift survey cluster sample (Yee, Ellingson & Carlberg 1996) was drawn from those Einstein Medium Sensitivity Survey (EMSS) clusters with $L_x \geq 1 \times 10^{44}$ erg s^{-1} in the 0.3 to 3.5 Kev passband. We restricted the CNOC sample to the redshift range $0.18 \leq z \leq 0.55$ for observational reasons.

The CNOC survey measured velocities of the cluster galaxies and their Gunn r-band luminosities (Carlberg *et al.* 1996). The EMSS observational quantity is the X-ray flux in the "detect cell", a 2.4 arcminute square aperture which is centered on the peak of the X-ray flux. In

this section we describe how we use the X-ray and optical data to measure a gas-to-light ratio.

2.1. Cluster Centers and Temperatures

The cluster centers have both X-ray and optical estimators, which should be consistent with the same location for the calculation of the gas-to-light ratio. The X-ray centers of Gioia *et al.* (1990) are defined as the peak of the X-ray flux and have an accuracy of 50 arcseconds. We adopt the location of the Brightest Cluster Galaxy (BCG) as the center of the optical light (Carlberg *et al.* 1996, Carlberg, Yee & Ellingson 1997) at the co-ordinates given in Gioia & Luppino *et al.* (1994) which have an accuracy of about 5 arcseconds. the X-ray and BCG co-ordinates have a mean difference of $33''$. The largest deviation comes from MS0906+11 which has a low significance difference of $58''$. We conclude that the X-ray centers and the BCG centers are statistically consistent with each other for our sample of rich clusters with large X-ray luminosities. We were unable to obtain a reliable velocity dispersion for the cluster MS0906+11 (Carlberg *et al.* 1996), so we will not include it in any of the following analysis.

The galaxy velocities are in equilibrium with the cluster potential and their distribution is consistent with tracing the mass distribution (Carlberg, Yee & Ellingson 1997, Carlberg *et al.* 1997a). If the X-ray gas is also in equilibrium and traces the potential, then the galaxies should have an equivalent temperature equal to the RMS X-ray temperature, T_x, derived from the spectrum. The velocity dispersion σ_1 implies a temperature $\Re T_\sigma/\mu = \sigma_1^2$, where $\Re$ is the gas constant and μ is the mean molecular weight of the gas. We find $T_\sigma = 10^8(\sigma_1/1180\,\mathrm{km}\,s^{-1})^2$ K for a gas that is 74% Hydrogen and 25% Helium by mass. The X-ray temperatures of nine of the CNOC clusters have been derived by Mushotzky and Scharf (1997, hereafter MS97). For the sample as a whole they find that the quantity $\beta = T_\sigma/T_x$ has a mean statistically equal to unity, as has been seen in other samples (*e.g.* Lubin *et al.* 1996).

To refine the agreement between T_x and T_σ we test whether the agreement is consistent within the errors, that is, besides predicting the mean of the distribution, we check for excess variance above the errors in the individual β values. We compare the ASCA derived T_x from MS97 (converting 1 Kev to 1.16×10^7 °K) to the T_σ estimated from the CNOC velocity dispersions. The error in β, ϵ_β, is calculated from quadrature sum of the jacknife errors of the velocity dispersions (Carlberg *et al.* 1996) and half of the MS97 confidence range of X-ray temperatures. The cluster with the greatest deviation, $2.1\epsilon_\beta$, is MS1455+22, which also stands out in the richness-velocity dispersion relation (Yee, private communication). In both cases the indication is that the cluster's true velocity dispersion is closer to ~ 900 km s^{-1} than to the $1170 \pm 150\,\mathrm{km}\,s^{-1}$ that we found (Carlberg *et al.* 1996). There are no strong indications that anything is particularly amiss, but there is no question that more cluster velocities would help clarify the situation for this cluster. For the nine clusters the average $\beta = 0.95 \pm 0.10$. The distribution has $\chi^2 = 15.3$ (or 11.1 without MS1455+22) which is about 9% (20%) probable, hence at this level we cannot reject the hypothesis that all β are equal to unity. Without MS1455+22 the mean $\beta = 0.87 \pm 0.08$. This is

possibly a very weak indication that the X-ray gas is somewhat hotter than the virial temperature of the total mass distribution. If true, this might be consistent with the gas being somewhat more extended than the mass (White *et al.* 1993, David, Jones, & Forman 1995).

2.2. Converting the Aperture Flux to a Gas Mass

The EMSS survey measures the X-ray flux, f_x in the 0.3-3.5Kev band in a 2.4 arcminute square on the sky. To determine the gas mass that is emitting this radiation we proceed as follows. The emitted luminosity in the $0.3(1+z)$ to $3.5(1+z)$ Kev band is $L_x = 4\pi d_L^2(z,q_0) f_x$, where $d_L(z,q_0)$ is the luminosity distance to the cluster. Above, we established that T_σ accurately predicts the X-ray temperature, so we will use T_σ to calculate the volume X-ray emissivity, $n_e n_H \varepsilon(T_\sigma)$, of the 14 EMSS/CNOC clusters. We will assume that the gas visible within the detect cell is isothermal. The spectral emissivity is calculated using the publicly available[8] Raymond-Smith code (Raymond & Smith 1977). We sum over the $0.3(1+z)$ to $3.5(1+z)$ Kev bins to give $\varepsilon(T_\sigma)$. The cluster metal abundances are taken to be 0.4 of the Allen (1973) values, to match approximately the metal abundances inferred for clusters. The mass density is $\rho = 1.24\times 10^{-24}\sqrt{n_e n_H/0.6}$ gm cm^{-3}.

We must assume a density profile for the cluster gas. A form which accurately fits most cluster's inferred X-ray gas profile is (Jones & Forman 1984),

$$\sqrt{n_e n_H}(r) = \frac{n_0}{1+(r/a)^2}, \tag{1}$$

where a is the core radius of the gas distribution, measured to be about $0.125h^{-1}$ Mpc (Jones & Forman 1984). We use $a = 0.125(\sigma_1/1000\,\mathrm{km}\,s^{-1})h^{-1}$ Mpc which takes into account the nearly linear increase of all scales with velocity dispersion (Navarro, Frenk & White 1996). The exact value of the core radius makes relatively little difference to the derived gas mass, typically about a 50% change for a factor of 4 in a, which is much greater than the expected range of a variation.

The X-ray luminosity from the part of the cluster in the detect cell is the projection along the line of sight of $\varepsilon(T)n_e n_H(r)$, integrated over the detect cell, which is a square with sides of physical length $2b$. That is, $L_x = 8\int_0^b\int_0^b\int_0^\infty n^2(r)\,dx\,dy\,dz$, where $r=\sqrt{x^2+y^2+z^2}$. With the aid of the Maple symbolic integrator,

$$L_x = n_0^2\varepsilon(T)\pi a^3\Big[\arctan\Big(\frac{ab}{b\sqrt{2b^2+a^2}+b^2+a^2}\Big) + \arctan\Big(\frac{a}{\sqrt{2b^2+a^2}}, \frac{b\sqrt{2b^2+a^2}-b^2-a^2}{b\sqrt{2b^2+a^2}}\Big)\Big], \tag{2}$$

where $\arctan(y,x)$ has a range of $[-\pi,\pi]$ to give the result in the correct quadrant. Given the measured L_x, we use Eq. 2 to derive n_0, the central gas density of the cluster. Then the gas mass

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[8]Version with last modification Sept 21, 1993, from ftp://heasarc.gsfc.nasa.gov/software/plasma_codes/raymond

projected in the detect cell is

$$M_{gas} = 4\pi\rho_0 a^2 b \int_0^1 \mathrm{arcsinh}\Big(\frac{1}{\sqrt{x^2+(a/b)^2}}\Big)\, dx, \tag{3}$$

which is easily integrated numerically.

The inferred central gas density, n_0, of Equation 1, is shown against the redshift of the cluster in Figure 1. The values are consistent with what is seen in other samples at low redshift. Not surprisingly, there is no detectable evolution (Carlberg *et al.* 1997b, MS97) nor clear correlations with other quantities.

2.3. The Gas-to-Light Ratio

It is straightforward to sum the selection function weighted luminosities of the galaxies within the bounds of the detect cell over the redshift range which contains the cluster galaxies. We have previously demonstrated that the galaxy number profile, as selected in the k-corrected Gunn r band (hence reasonably insensitive to the color differences between cluster and field galaxies) has a distribution which is statistically identical to the total mass distribution (Carlberg, Yee & Ellingson 1997, Carlberg *et al.* 1997a). There is detectable evolution of both the cluster and field galaxies over the redshift range we have observed (Schade *et al.* 1996a, 1996b, Lin *et al.* in preparation). The Gunn r data are acceptably described for ($q_0 = 0.1$) with pure luminosity evolution and no density evolution, at the rate of about 1 ± 0.5 magnitude per unit redshift. In this system the field luminosity density, integrated to $L = 0$ using the fitted luminosity function (as is the cluster, so the correction has no net effect), is constant and is equivalent to $\rho_c/j = 1543 \pm 283h\,\mathrm{M}_\odot/\,\mathrm{L}_\odot$.

The Schechter luminosity function fits find that cluster and field galaxies are brightening at approximately at the same rate with redshift. However the galaxy populations are different and we must allow for the differential evolution between cluster and field galaxies. Most of the cluster galaxies were former field galaxies that were accreted onto the cluster with effectively no starbursting, but a rapid suppression of the star formation (Abraham *et al.* 1996, Balogh *et al.* 1997). By computing average luminosities we find that cluster galaxies are faded about 0.11 ± 0.05 mag in Gunn r relative to the field (Carlberg *et al.* 1996) which we adopt as our correction. A slightly larger fading of about 0.3 ± 0.1 mag is seen in the rest frame B band (Lin *et al.* in preparation) as is to be expected for the 0.2 mag average color difference between field and cluster galaxies (for details, see Carlberg, Yee & Ellingson 1997). However, because the bright galaxy population within these very rich clusters is similar to these galaxies, the "detect cell" galaxies have properties similar to the cluster galaxies as a whole. Another approach to estimating the differential evolution is to model the evolution of the galaxies in color and magnitude. Using the Bruzual & Charlot GISSEL package (1993 and revisions) we find that for the observed $\Delta(g-r)_z = 0.2$ mag color difference between the field and the cluster the expected

fading is $\Delta M_r \simeq 0.4$ mag for galaxies with a fairly wide range of star formation histories prior to their termination in the cluster. The difference between the fading from the model and the measured luminosity difference could be taken as an indication that cluster galaxies are about 30% more massive than field galaxies, possibly as a result of merging, however this requires further examination. Except for this differential evolution correction our survey measures the luminosities of field and cluster galaxies at the same time so that the selection functions and most corrections are in common and simply cancel in the Ω calculation.

The fractional errors of the gas-to-light ratios are similar numbers, whereas the absolute errors correlate with the values themselves. We must therefore calculate the averages and variances using the logarithms of the gas-to-light ratios. The χ^2 of the Ω_{gas} values about their mean is $\chi^2 = 20.8$, which for 13 degrees of freedom is about 8% probable, suggesting that there may be a further source of variance beyond the error distribution alone. There are no significant correlations in these data between Ω_{gas} and L_x or σ_1, however, there is a significant correlation with redshift. The natural physical interpretation of this redshift correlation is that it is an "aperture effect". Clusters at low redshift are known to have an increasing gas-to-mass ratio with increasing radius (David, Jones, & Forman 1995, White & Fabian 1995). There is strong evidence that clusters at fixed T_x or T_σ have little evolution in their X-ray properties with redshift (Carlberg *et al.* 1997b, MS97). Moreover, the CNOC clusters have a constant mass-to-light ratio (evolution corrected luminosities, Carlberg *et al.* 1996, Carlberg *et al.* 1997d). Hence, we would expect that clusters at higher redshift, which have a larger physical radius within the fixed angular size of the detect cell aperture, will have higher Ω_{gas} values than those at low redshift.

The aperture correction for gas-to-light ratio is relatively small and stable. We do not try to extrapolate either the gas mass or the light to larger radii, but only seek to normalize our results to a mean interior overdensity, δ, of $500\rho_c$ (Evrard 1997) using a simple fit to the gas-to-total mass profiles of David, Jones & Forman (1994). From their derived cluster gas to mass profiles we estimate that $f_g(500) = f_g(\delta)/[1 - 0.35 \log(\delta/500)]$. The calculated overdensities range from about 700 to about 7000. The resulting average correction is about 30%, with the largest correction being 66%. With this correction the $\chi^2 = 16.8$ for 13 degrees of freedom, which is entirely consistent with no variance beyond the errors. This correction is an important element which will be better determined from X-ray imaging studies of these clusters (Lewis *et al.* in preparation).

In Figure 2 we display the corrected $\Omega_b = \Omega_{gas} + \Omega_*$. We have estimated the stellar baryons as having $\Omega_* = 0.003h^{-1}$, on the basis of an average mass-to-light ratio of approximately $5\,\mathrm{M}_\odot/\mathrm{L}_\odot$ (Mihalas & Binney 1981) and our closure value of approximately $\simeq 1500h\,\mathrm{M}_\odot/\mathrm{L}_\odot$. The average $\Omega_b = 0.019 \pm 0.02$ for our measured 0.11 mag luminosity differential between cluster and field. This Ω_b is equivalent to an $\eta = 4.0 \times 10^{-10}$ (for $h = 1$). Although it is a "mid-range" value, it is within the statistical errors of Tytler, Fan and Burles (1996). For the 0.4 mag of fading, our results are just beyond their 2σ confidence range, and comparable to the lower Ω_b generally derived from Helium (Hogan, Olive & Scully 1997, Schramm & Turner 1997).

3. Discussion and Conclusions

The average of the 14 Ω_b values is 0.019 if the fading of field to cluster galaxies is the 0.11 mag, as derived from the luminosities of the galaxies in our sample, or, $\Omega_b = 0.015$, based on the predicted 0.4 mag fading derived from stellar population modeling of the color difference between the field and cluster galaxies. These values are in the mid range of the current values, but remains consistent with the high values (Tytler, Fan & Burles 1996). The random error is 12%, considerably less than the systematic uncertainties. For $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ $\Omega_b = 0.040-0.051$. The individual clusters are corrected for the average internal segregation of gas and mass in which the gas is more extended than the mass. Our Ω_b value is calculated for clusters at a mean redshift of 0.31, taking $\Omega_M = 0.2$ and $\Omega_\Lambda = 0$. If this low density universe has an $\Omega_\Lambda = 0.8$, the Ω_b are reduced about 24%. The random error in the result is 12% whereas the potential unresolved systematic errors are about 30% and dominate the error budget. The distribution of the corrected gas-to-light ratio values about the mean has $\chi^2 = 16.8$ for 13 degrees of freedom, which is consistent with there being no intrinsic variation of the gas-to-light ratio from cluster to cluster, beyond the mean variance of 40%. This reinforces one of the benefits of the gas-to-light ratio estimator, which is that projection effects have relatively little effect. The lack of variation in the aperture corrected gas-to-light ratio from cluster to cluster, over quite a large range in redshift, constrains any significant possibilities for a large scale segregation of gas and light (or by extension, gas and mass) external to the clusters. The greatest weakness of this measurement is that the X-ray fluxes are not measured much beyond the cores of the clusters. X-ray data extending to larger radii (Lewis *et al.* in preparation) will reduce the aperture correction and reduce the error in estimating the enclosed optical luminosity.

Eventually an overall consistency of the cosmological parameters as measured from various sources will pin them down, and the biases in their measurement. For instance, if the relatively low value of $\Omega_b \simeq 0.012$ from Helium (Hogan, Olive & Scully 1997) is accepted as the correct value, then we would conclude that correction for the fading of field galaxies to cluster galaxies is the 0.4 mag estimated from the colors and consistency with the luminosity functions likely requires that cluster galaxies are on the average about 30% more massive (from, say, merging) than field galaxies. A test of this will soon be possible using the CNOC field sample of galaxy groups whose galaxies much more closely resemble the general field population. The errors in the Ω_{gas} values will soon be reduced as X-ray imaging data become available for these clusters.

To test whether the baryons in the stars of the cD are uncorrelated with the gas in the central region, we omit the light of the cD galaxy from the gas-to-light ratio. The variance of the Ω_b values then increases by a factor of three, such that the χ^2 strongly indicates that the gas-to-light ratios are showing a significant variation. We conclude that the cD is statistically coupled to the central gas of the cluster. Moreover, given the stability of the gas-to-light ratio from cluster to cluster and with redshift, the conversion efficiency of gas to stars (in cluster galaxies) is constant from place to place, within the 40% errors of our measurement.

Many of the elements of the calculation of Ω_b are in common with our calculation of Ω_M, which found $\Omega_M = 0.19 \pm 0.06$. The alternate field-to-cluster fading of 0.4 mag would lower this value to $\Omega_M = 0.15 \pm 0.05$. Any as yet uncovered systematic error in common to the two will cause the two values to rise or fall together. Consequently, the possibility that $\Omega_M = 1$ seems remote, since it would demand that either Ω_b is about 5 times larger than we find here or that there be a very substantial segregation between dark matter and hot gas, opposite in sign to what would be expected. That is, the dark matter, generally supposed to be cold on the basis of the power spectrum of density fluctuations (*e.g.* Peacock & Dodds 1994) be kept out of these high velocity dispersion clusters, whereas the X-ray plasma, known to be at least as hot as the cluster mass field, would have to be retained or even enhanced within the clusters.

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Fig. 1.— The central density, n_0, inferred from the X-ray flux for the 14 EMSS/CNOC clusters versus the redshift.

Fig. 2.— The aperture corrected estimate of Ω_b with the stellar mass included, plotted against the cluster redshift. This distribution is consistent with a single universal value of Ω_b. The variance weighted mean of the logarithmic distribution, $\Omega_b = 0.019$ and the population variance are shown for a field to cluster fading of 0.11 mag. The error in the mean is about 12%.

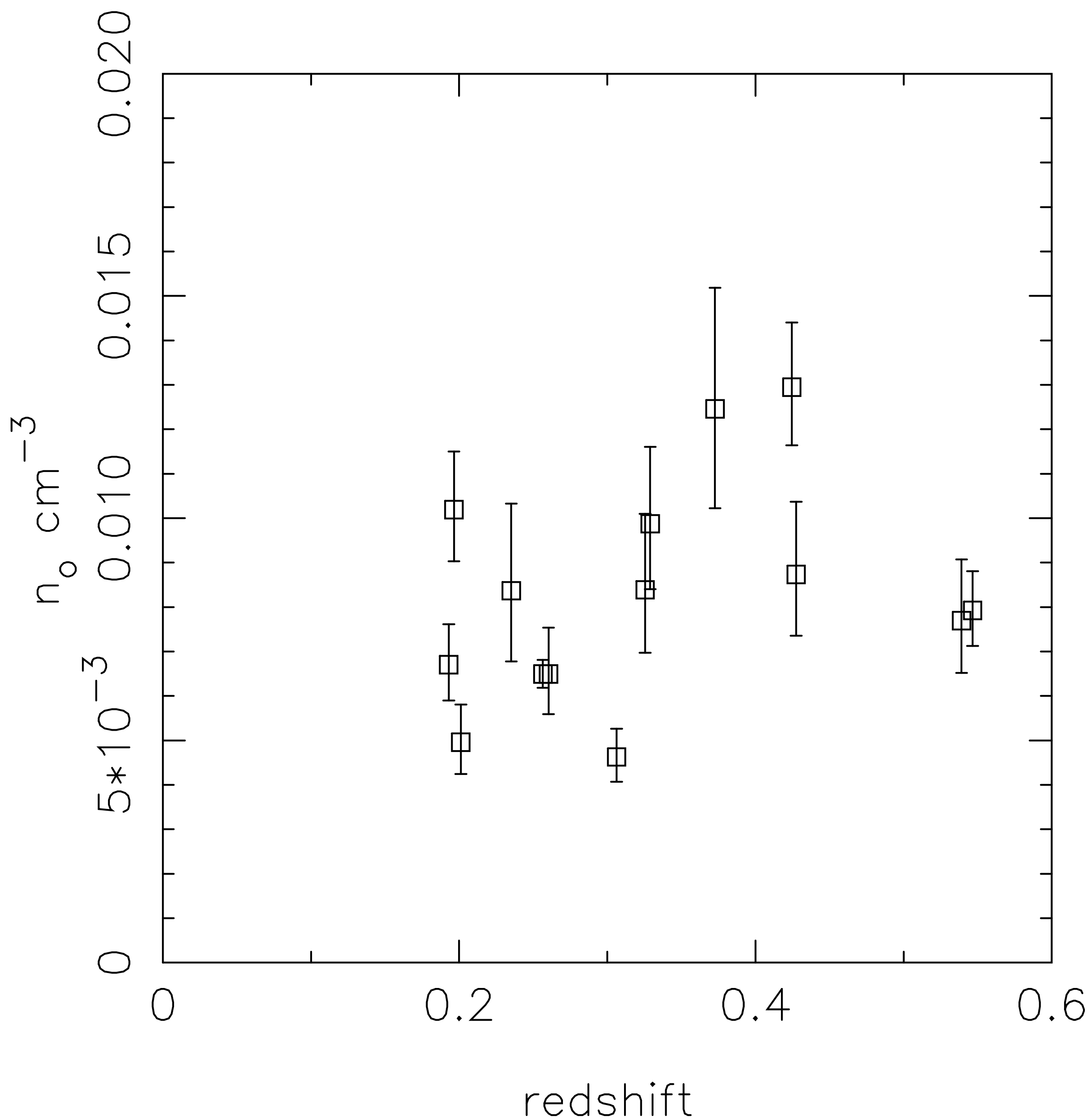

Fig. 1.—

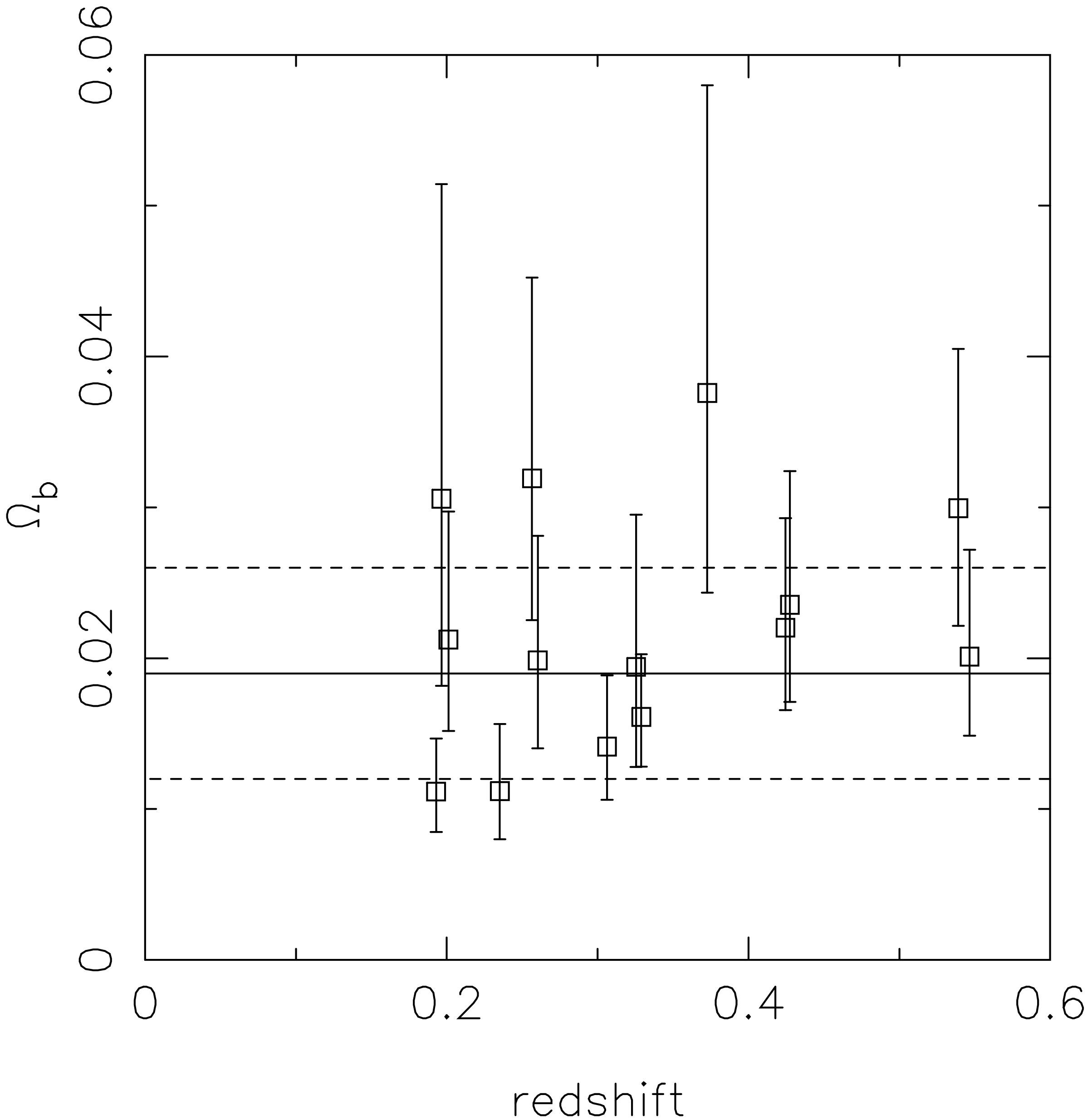

Fig. 2.—